

# Strategic roadmap

## Search for Earthlike planets

presentation by Roger Angel, Tucson February 15 2005

- Direct imaging is preferred method for detection of nearest examples, as well as required for spectroscopic follow up
- The strategic roadmap must have direct imaging as its overarching goal
- The main challenge is seeing the planet against the starlight halo
- We need to develop as much deep understanding and experience as we can because TPF represents such a huge advance
- Gain needed is factor 100,000 x 5 on present best
- For reference, SIM is factor 1000 gain on classic astrometry

# Physics lesson

- What controls starlight at any point in the focal plane is the
  - Sum of little arrows (Feynmann)
  - Fourier transform of complex amplitude in pupil plane (Fresnel-Huygens)
- If you know the complex amplitude (amplitude and phase) of the (monochromatic) speckles at any point in the focal plane, you can modulate a deformable pupil mirror to create an anti-speckle
  - Same as 1 and -1 order of diffraction grating
  - Speckle is cancelled out
  - -1 order appears opposite, and won't be right unless errors are pure phase
  - Over half field, halo can be cancelled regardless of origin (figure or diffraction)

# Focal plane interferometer

- Phase shift method gives complex amplitude directly
  - Proven method for shop metrology method
- Interfere focal plane with spare light from star image core

imaging sensitivity. Here we describe two ways to take advantage of narrow bandpass and to obtain better control of systematic errors. Multiple images are formed in 10% bandwidth and recorded by coronagraphic interferometers equipped with act and/or amplitude. In one method, a single deformable pupil mirror is used to address both phase and wave-front components of the halo. This yields good diffraction suppression with high throughput over half the focal plane. In a second method, the coronagraph is a second stage after conventional apodization. The halo from uncontrollable residual wave front is removed by destructive interference made directly at the detector by a reference wave synthesized by spatial light modulators in the reference arm of the interferometer. It may be achieved by control elements with greatly relaxed, and thus achievable, tolerances. Systematic errors are minimized because the planet imaging cameras themselves provide the calibration data.

*Subject headings:* instrumentation: adaptive optics — planetary systems — stars: techniques: interferometric

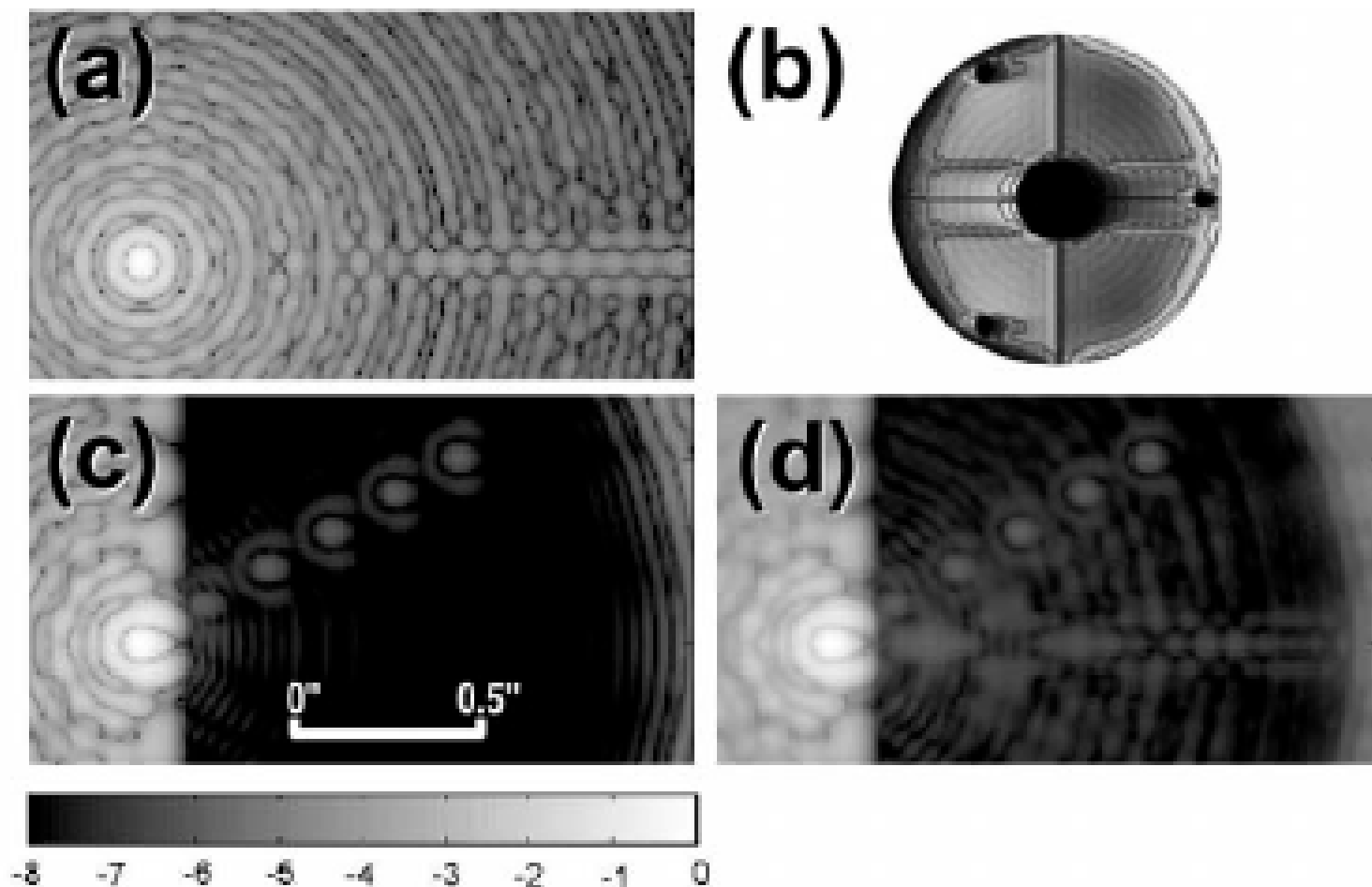
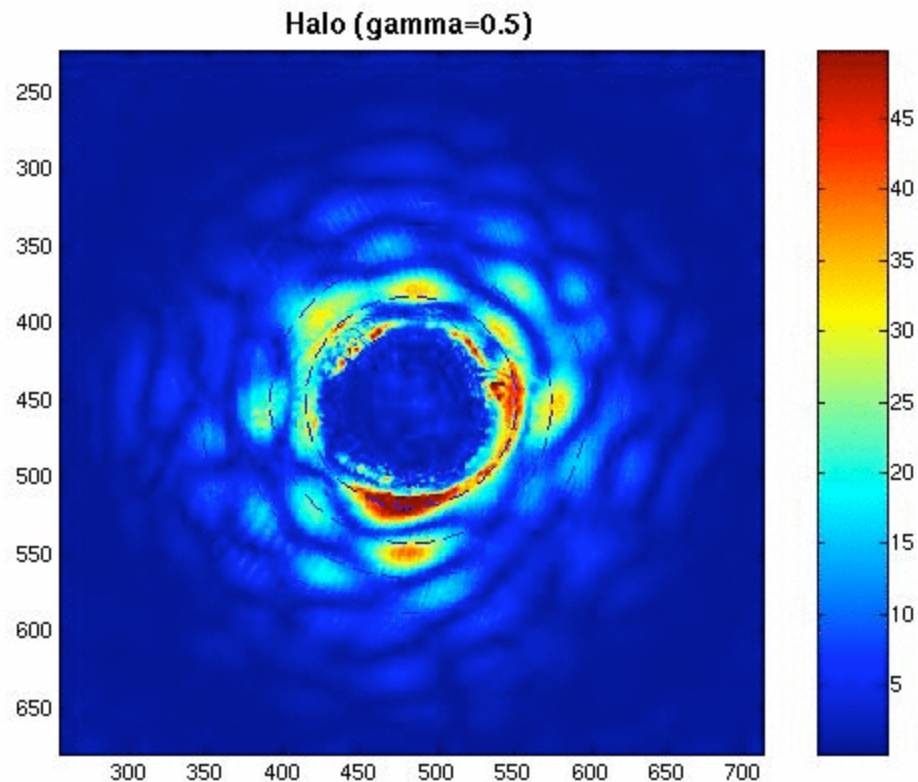


FIG. 2.—Correction of the *HST* diffraction halo by pupil phase adjustment. (a) Diffraction pattern at wavelength  $0.5\ \mu\text{m}$  over eight decades, given ideal figure correction. (b) Pupil phase change required to correct for diffraction, optimized for field radius  $2.5\text{--}35\ \lambda/D$ . The contour interval is  $\pi/4$ . (c) Monochromatic point-spread function (PSF) after correction. Companions at  $10^{-6}$  star are revealed at radial separations in  $0.2''$ . (d) PSF at spectral bandwidth of 10%.

# Closed loop psf shaping in Lab



AO closed loop from focal plane measurements with coronagraphic interferometer

Wavefront shaping with 140 element Mems DM

Commands from complex amplitude of halo measured by phase shifts of interferometer reference beam

Starting point is deliberately aberrated PSF with  $\sim 70\%$  Strehl

(Codona, Angel, Putnam)

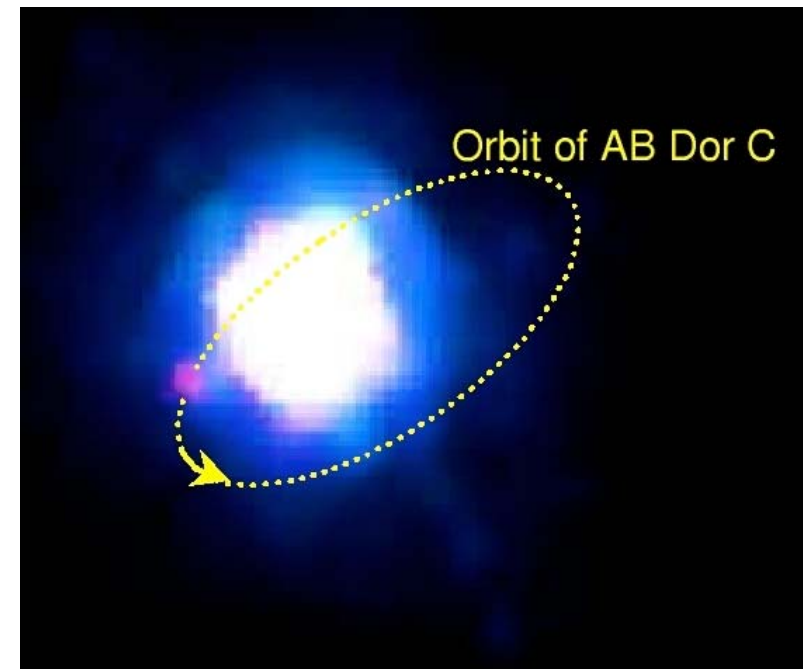
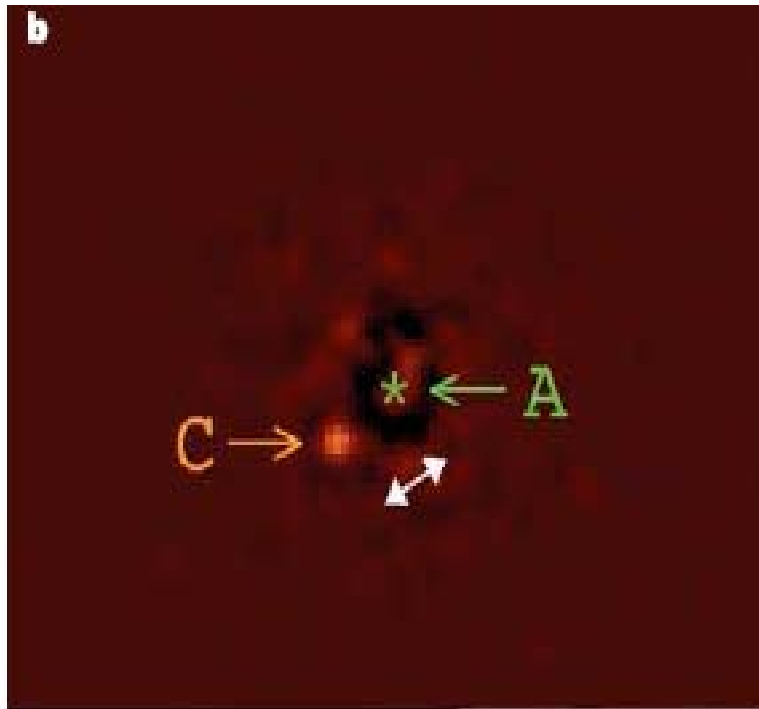
# Also afterburner concept

- Get best result from classic suppression methods (coronagraphy)
- Measure residual speckles complex amplitude
- Create explicit anti focal plane with double dm (phase and amplitude)
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# Ground development of near IR high contrast imaging

- 8m VLT + AO holds record for close companion imaging (Close et al)

Close et al, AB Dor C at contrast 100, 0.156 arcsec separation

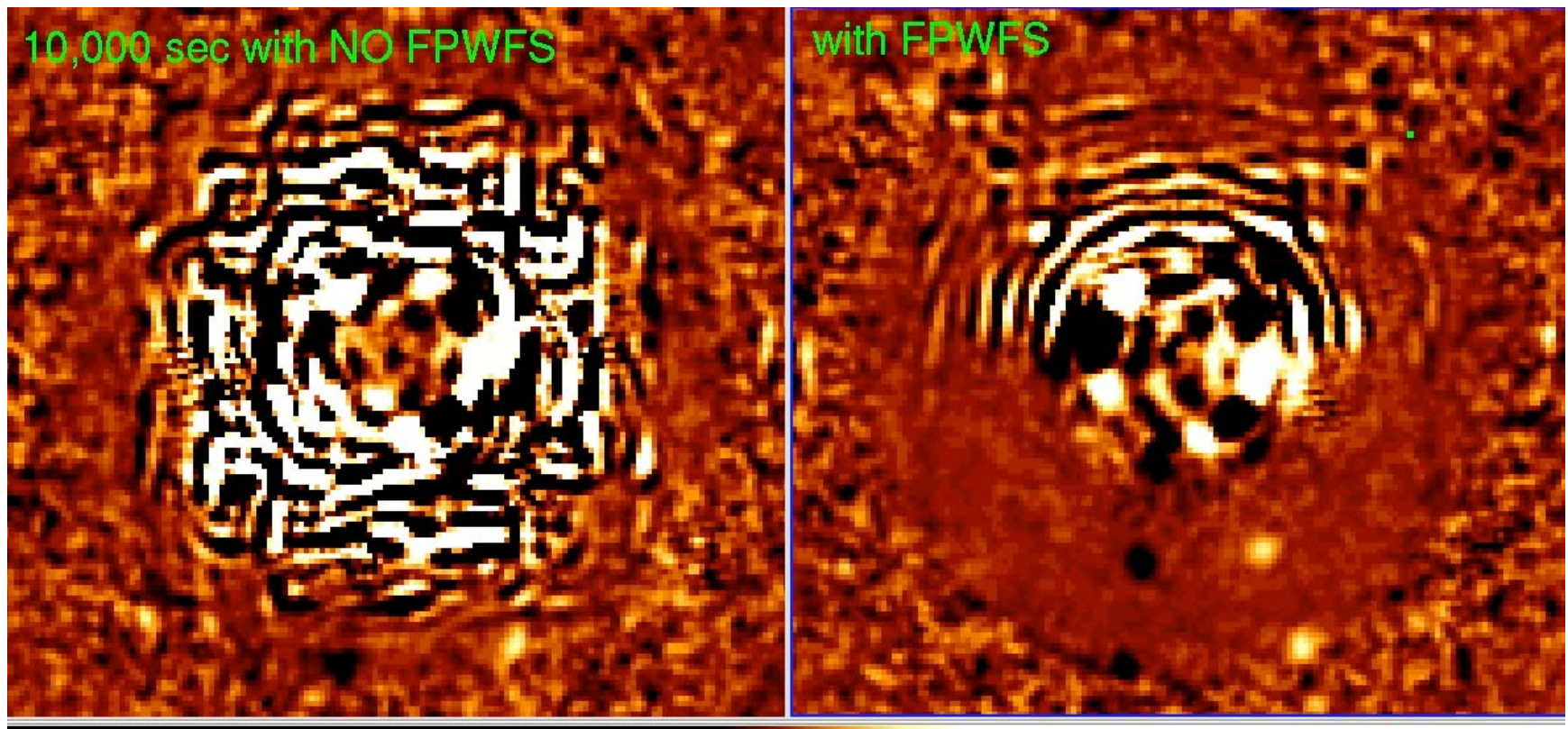


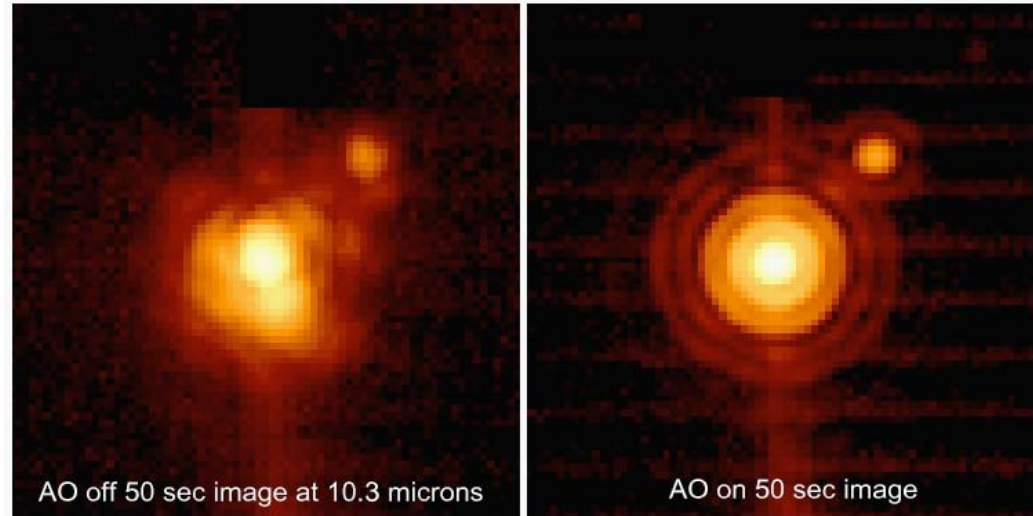
**Figure 1** Discovery image of AB Dor C with the NACO SDI high contrast camera. **a**, The 1.625- $\mu\text{m}$  image. **b**, The SDI of the 1.625–1.575- $\mu\text{m}$  images illustrates how the SDI camera enables the subtraction of the scattered light from AB Dor A to reveal the significantly redder source AB Dor C (contrast enhanced in **b**). The white scale bar is the system separation of just 0.156". Both images have had the lowest spatial frequencies removed (unsharp-masked) to help highlight the 'point-like' sources in the field. AB Dor C is the faintest companion ever imaged within 0.16" of a star.

Full simulation of 8 m AO with focal plane interferometer by Codona and Close.

Companions at  $10^{-6}$ ,  $0.4''$  and  $0.6''$

on right with correction by deformable mirror from complex amplitude measured in focal plane



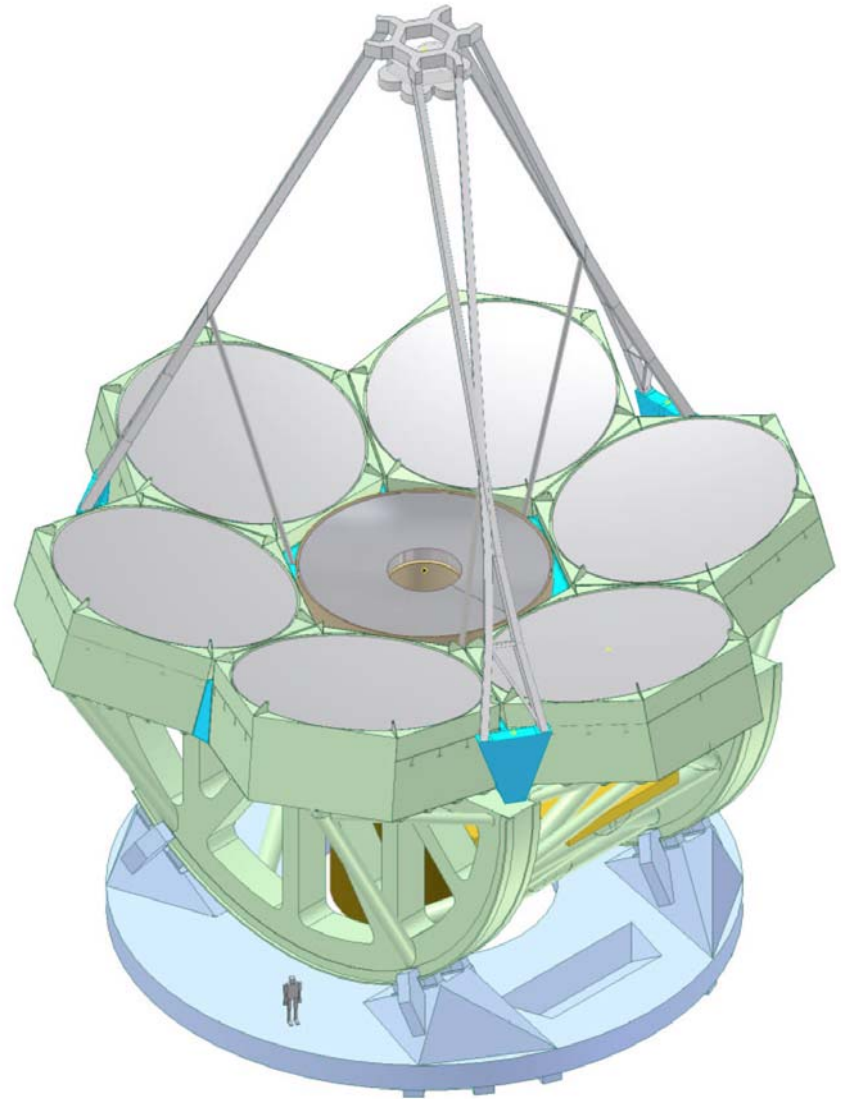


Correction of stellar thermal images ( $10\text{ }\mu\text{m}$ ) with the MMT deformable secondary. With the AO system on (right) a Strehl of 96% is obtained. The measured emissivity is 7%.

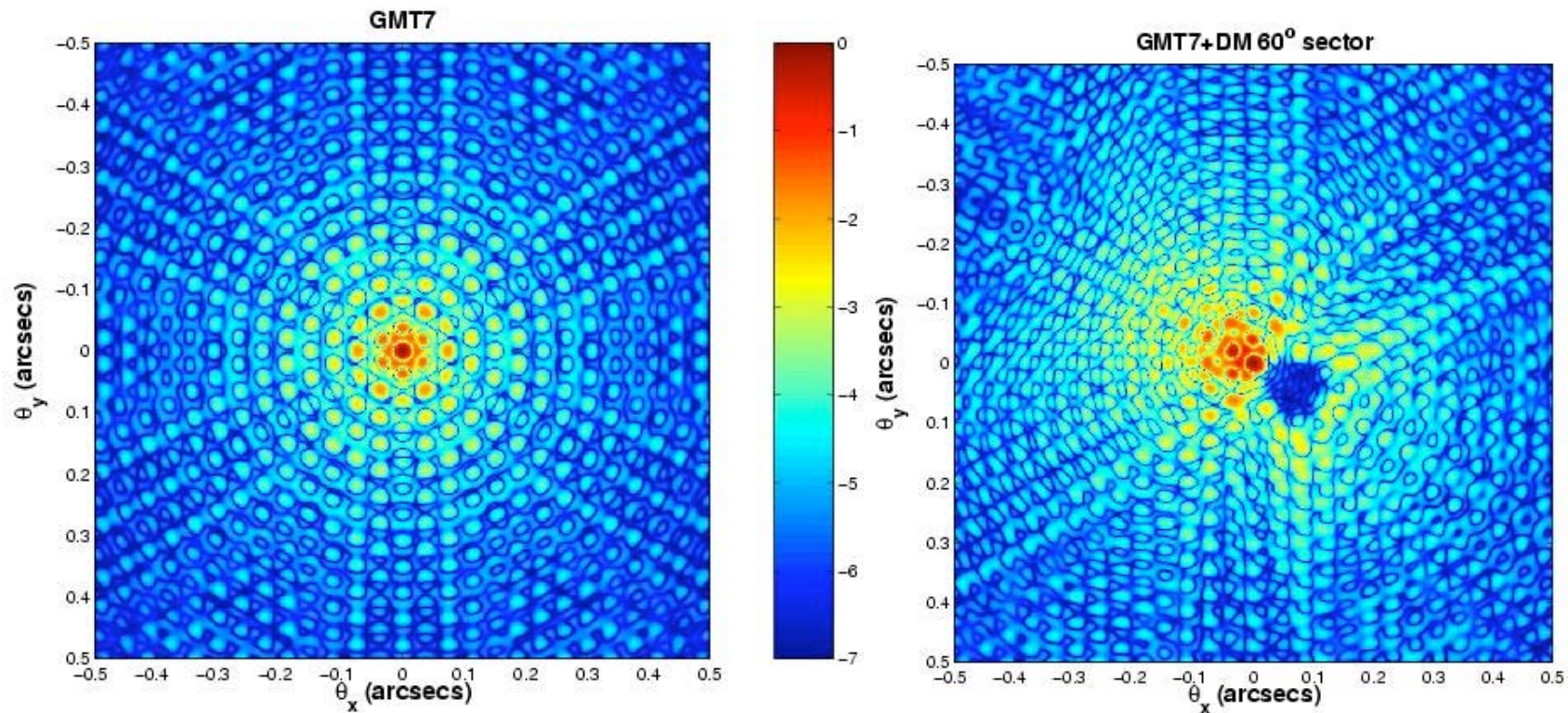
MMT deformable secondary. The 64 cm diameter mirror is sky-baffled and has 336 actuators

# Antarctic copy of GMT

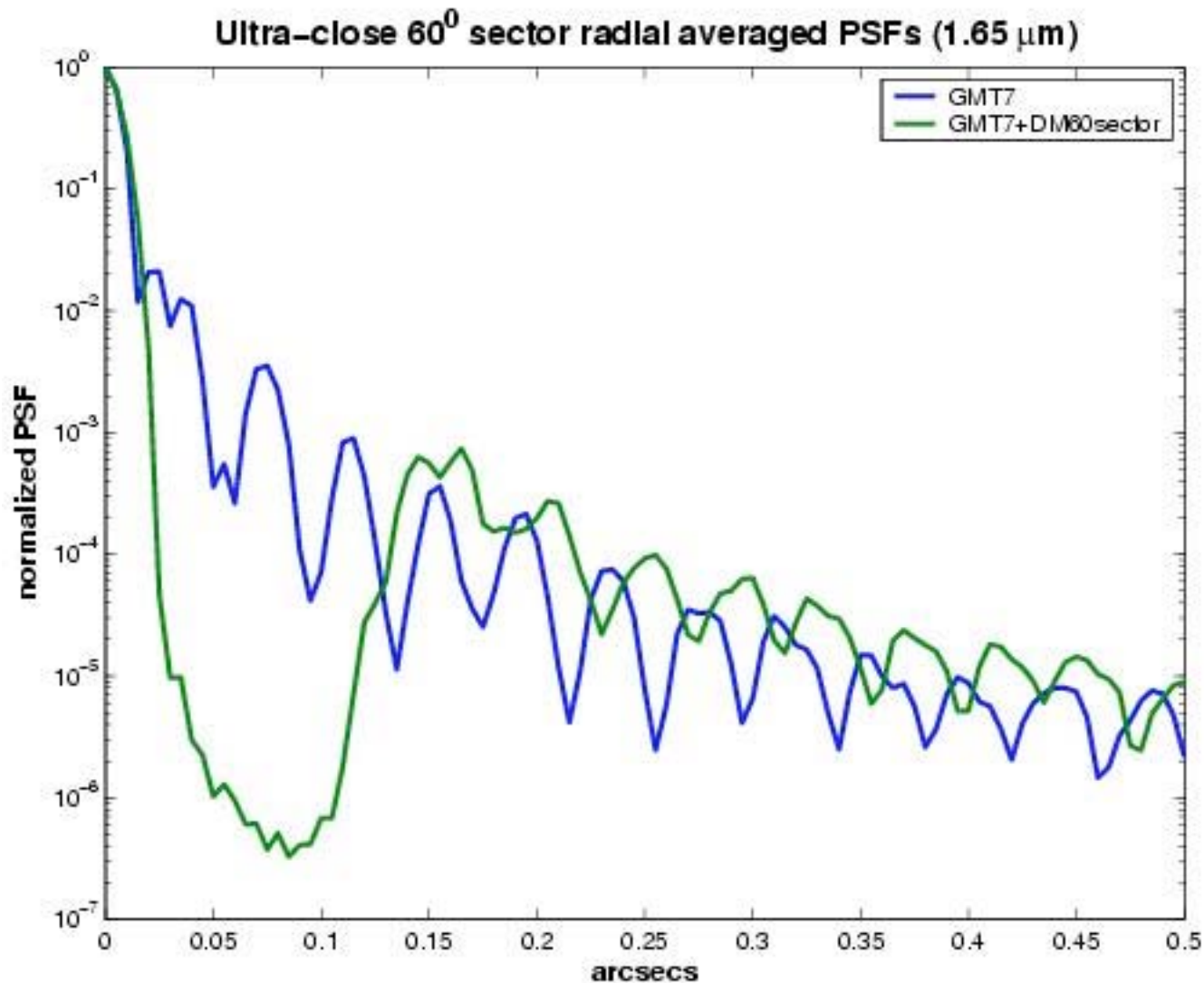
- GMT has very high imaging performance
- Very low thermal background with AO by deformable secondary
- Building a copy of an existing GMT in Chile will minimize trouble on site



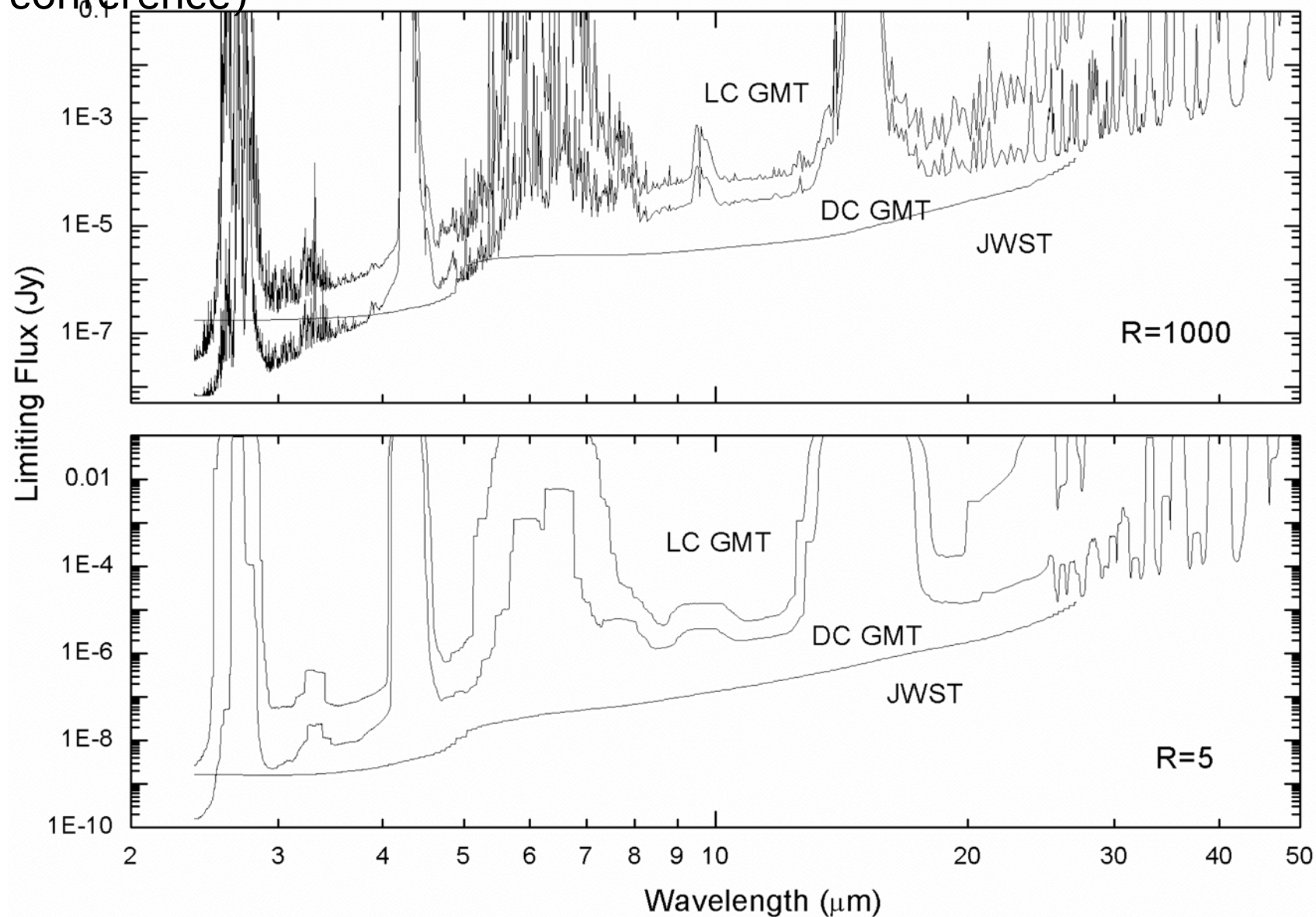
# Raw and shaped PSFs



# Radial average over 60 degree sector



GMT and JWST point source sensitivity for  $\lambda > 2.5$  mm,  
10s,  $10^5$  sec      Angel, Lawrence and Storey, 2003 Backaskog  
conference)



# Hubble paradigm for TPF-C:

- Use telescope with continuous filled aperture to avoid diffraction at segment edges
  - Off axis primary to avoid diffraction of secondary and spider
  - Make with super-diffraction limited figure
  - Strong apodize for achromatic suppression of diffraction-coronagraphic field and Lyot stops
  - NASA supplies planet photons to science community who will compete to make instruments
- This is probably wrong

# Solution for inevitable figure errors may take care of second order diffraction errors transparently

Segmented on-axis mirror may be just fine

Bigger is MUCH better, segmentation allows breaking of 3.5 m shroud barrier

# Preferred solution

- Complete integration of telescope/PSF control and science instrument
  - Multiple imaging cameras in  $\sim 2\%$  bandwidth
  - Combine functions of speckle phase sensing and science camera
  - Feedback to deformable mirror correction of residues from diffraction and figure errors

# Is space uniquely capable of Earth-like planet detection

- No
- Optical and infrared detection possible with very large ground apertures.
- Sharper diffraction of much bigger aperture
  - Greatly helps diffraction problems
  - Can overcome higher background
- 100 m (eg OWL) at dome C (BOWL, FOWL) can duplicate sensitivity of TPF-C and TPF-I

# recommendations

- NASA should coordinate with, and support, ground coronagraphy efforts, just as it does ground interferometry
- TPF should be seen in landscape of exoplanet studies, a broad and scientifically rich new field
- In near future LBT with low background, high resolution deformable secondaries is ideal for coronagraphy as well as nulling interferometry
- Further off, but in your horizon, large antarctic telescope plans must be integrated with responsible road-map planning
- Involve the broad US community (i.e. fund research) in the main problem of innovating and developing the best system for star suppression. Expertise as well as ideas need to be encouraged in academia
- Planet imager - for heaven's sake don't endorse any expenditure in technology aimed at this, unless and until there is a concept that is remotely credible